(19) Eur päisches Patentamt .
European Patent Office
Office européen des brevets

(11) EP 0 860 600 A2

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
26.08.1998 Bulletin 1998/35

(51) Int. Cl.^{6}: F02D 41/38, F02D 41/20

(21) Application number: 98102890.5

(22) Date of filing: 19.02.1998

(84) Designated Contracting States:
AT BE CH DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: 21.02.1997 JP 37979/97
26.02.1997 JP 42411/97

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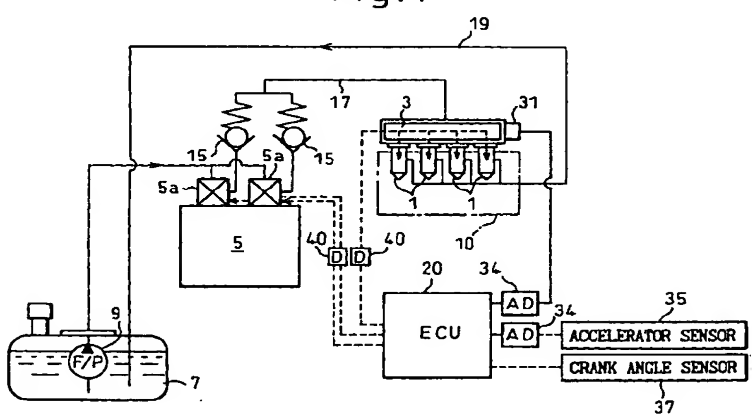
(54) A fuel injection system for an internal combustion engine

(57) Fuel injection valves (1) of the engine (10) are connected to the common rail (3). The high pressure fuel pump (5) supplies pressurized fuel to the common rail (3). The electronic control unit (ECU) (20) determines whether one or more of the fuel injection valves has failed. When one or more of the fuel injection valves is determined as having failed, the ECU stops the high pressure fuel pump and injects fuel from all of the fuel injection valves including the fuel injection valve determined as being failed. Since the fuel remained in the common rail is expelled from the common rail through, not only the failed fuel injection valve, but also other fuel injection valves, the common rail is depressurized in a short time and, thereby, the abnormal fuel injection from the failed fuel injection valve stops in a short time.

Fig. 1



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Description

TECHNICAL FIELD

The present invention relates to a fuel injection system for an internal combustion engine, and particularly, to a fuel injection system including means for detecting a failure of the fuel injection system.

BACKGROUND ART

A common rail type fuel injection system for an internal combustion engine is known in the art. A common rail type fuel injection system includes a common rail which stores high pressure fuel fed from a high pressure fuel pump. Fuel injection valves for the engine are connected to the common rail to inject the high pressure fuel in the reservoir (i.e., the common rail) into the respective cylinders of the engine. Namely, the common rail acts as a reservoir which stores high pressure fuel and distributes it to the respective fuel injection valves.

Further, a common rail type fuel injection system provided with means for detecting a failure thereof, such as leakage from the common rail or sticking of the fuel injection valves, is also known.

This kind of the common rail type fuel injection system is, for example, disclosed in Japanese Unexamined Patent Publication (Kokai) No. 8-4577.

The fuel injection system in the '577 publication is provided with a pressure sensor for detecting the pressure in the fuel in the common rail and measures the difference between the pressures in the common rail before and after each fuel injection from the fuel injection valves, i.e., the pressure drop in the common rail during the fuel injection period. Further, the system in the '577 publication is provided with failure detecting means for estimating the pressures in the common rail before and after the fuel injection based on the operating condition of the engine and the bulk modulus of elasticity of the fuel in the common rail in order to estimate the pressure drop during the fuel injection period. The failure determining means determines that the fuel injection system has failed when the difference between the measured pressure drop and the estimated pressure drop is larger than a predetermined reference value.

In the system of the '577 publication, the estimated pressure drop ΔP caused by one fuel injection is calculated by $\Delta P = (K/V) \times Q$ where Q is a fuel injection amount determined from the operating condition (the load condition) of the engine, K is a bulk modulus of elasticity of the fuel and V is a total volume of a high pressure part of the fuel injection system including the common rail, the a high pressure supply line to the common rail and of a fuel injection line from the common rail to the fuel injection valves. In the '577 publication, constant values are used for the bulk modulus K and the volume V. Namely, it is considered that the pressure drop during the fuel injection period equals the pressure drop caused by the fuel flowing out from the common rail. Therefore, if the amount of fuel actually flowing out from the common rail during the fuel injection period is the same as the fuel injection amount Q, the pressure drop during the fuel injection period must be the same as ΔP. If the estimated ΔP is different from the measured pressure drop, it is considered that the amount of the fuel actually flowing out from the common rail during the fuel injection does not agree with the calculated (i.e., target) fuel injection amount Q. For example, when the measured pressure drop is larger than the estimated pressure drop ΔP by a certain amount, this means that the amount of the fuel actually flowing out from the common rail is larger than the target value of the fuel injection amount. In this case, therefore, it is considered that a failure of the fuel injection system such as the sticking of the fuel injection valve at the opening position has occurred.

However, in the system of the '577 publication, it is difficult to determine a failure correctly when the pressure of the fuel in the common rail changes in a very wide range during the engine operation.

As stated above, the '577 publication assumes that the bulk modulus of elasticity K of the fuel is constant regardless of the pressure on the fuel. However, actually, the bulk modulus of elasticity K of the fuel changes in accordance with the pressure of the fuel. Therefore, in the actual system, the pressure drop during the fuel injection period takes different values even though the fuel injection amount is the same if the pressure of the fuel in the common rail change in a wide range. For example, since the bulk modulus of elasticity K of the fuel becomes larger as the pressure increases, the measured pressure drop increases as the pressure in the common rail increases even if the fuel injection amount is the same. Therefore, if a constant value of the bulk modulus of elasticity K is used for estimating the pressure drop ΔP, it is difficult to determine a failure of the fuel injection system correctly when the pressure in the common rail changes in a wide range.

It may be possible to prevent this problem to some extent if the reference value for the difference between the actual value and the estimated value of the pressure drop used for determining the failure is set to a relatively large value taking the change in the value of the bulk modulus into consideration. However, in a common rail type fuel injection system of a certain type, the pressure of the fuel in the common rail varies in a very wide range in order to control both the fuel injection amount and the rate of injection in accordance with the operating condition of the engine. For example, in some common rail type fuel injection system, the pressure in the common rail changes from about 10 MPa to 150 MPa. In such a common rail type fuel injection system, since the change in the bulk modulus of elasticity is very large, the

reference value must be set to a very large value in order to prevent a normal fuel injection system being incorrectly determined as having failed and, in this case, the determination of the system becomes practically impossible.

Further, in some failures, for example, a failure in which the fuel injection valve sticks at the opening position, damage to the engine may occur. When one or more of the fuel injection valve sticks at its opening position, the fuel injection valve continues to inject fuel into the cylinder, and the maximum cylinder pressure may become excessively high due to the combustion of a large amount of fuel. This may shorten the service life of the engine and, in an extreme case, cause damage to the engine.

To prevent this from occurring, for example, Japanese Unexamined Patent Publication (Kokai) No. 2-112643 discloses a common rail type fuel injection system provided with means for preventing damage to the engine even if the fuel injection valve has failed.

The common rail type fuel injection system in the '643 publication includes a plurality of common rails (reservoirs), a plurality of fuel injection valves connected to the respective common rails and a plurality of fuel pumps for feeding fuel to the respective common rails. When a fuel injection valve is determined as having failed, fuel feed from the fuel pump to the common rail connected to the failed fuel injection valve is stopped. By stopping the fuel feed to the common rail, the fuel injection from the failed fuel injection valve ceases after all the fuel remained in the common rail is injected into the cylinder. In the fuel injection system of the '643 publication, the abnormal fuel injection from the failed fuel injection valve ceases in a relatively short time and the period in which the engine is exposed to a high maximum cylinder pressure becomes relatively short even when the fuel injection valve has failed and, thereby, the possibility of damage to the engine is lowered.

In the system of the '643 publication, however, the abnormal fuel injection does not cease until the pressure in the common rail becomes sufficiently low, i.e., all the fuel remained in the common rail is injected into the cylinder through the failed fuel injection valve. The amount of the fuel remained in the common rail becomes larger as the pressure in the common rail increases. As explained before, the pressure in the common rail becomes about 150 MPa in some common rail fuel injection system. In this case, the amount of the fuel in the common rail becomes very large even if the volume of the common rail is relatively small. In this case, therefore, the fuel injection from the failed fuel injection valve continues until the large amount of the fuel remained in the common rail is injected into the cylinder and the period in which the engine is exposed to an excessively high maximum cylinder pressure may be long. Thus, in some cases, the possibility of damage to the engine cannot be reduced.

In order to prevent this problem, the fuel injection from the failed fuel injection valve must be immediately stopped. However, when a fuel injection valve has failed, it is generally difficult to stop the fuel injection. For example, if the fuel injection valve stays at its opening position due to a failure of the control device or a short circuit of a fuel injection circuit, the fuel injection from the failed fuel injection valve cannot be stopped by electrical control. Further, if the failure is caused by sticking or locking of the moving elements of the fuel injection valve caused, for example, by the entry of foreign matter, the fuel injection also cannot be stopped by electrical control.

DISCLOSURE OF INVENTION

In view of the problems in the related art as set forth above, one of the objects of the present invention is to provide means for stopping the fuel injection from the failed fuel injection valve in order to shorten the period in which the engine is exposed to a high maximum cylinder pressure when one or more of the fuel injection valves is determined to have failed.

Another object of the present invention is to provide means for correctly determining the failure of the fuel injection system without being affected by the change in the bulk modulus of elasticity of fuel even if the pressure of the fuel varies in a very wide range.

According to one aspect of the present invention, there is provided a fuel injection system for an internal combustion engine comprising a reservoir for storing pressurized fuel, fuel injection valves connected to the reservoir and injecting fuel in the reservoir into an internal combustion engine at a predetermined timing, a fuel pump for feeding pressurized fuel to the reservoir at a predetermined timing in order to maintain the pressure of the fuel in the reservoir at a predetermined value and failure determining means for determining, for each of the fuel injection valves, whether it has failed, characterized in that the fuel injection system further comprises fuel feed cut means for stopping the fuel feed to the reservoir from the fuel pump when the failure determining means determines that any of the fuel injection valves has failed, and depressurizing means for discharging the fuel in the reservoir to the outside of the reservoir when the failure determining means determines that any of the fuel injection valves has failed.

According to this aspect of the invention, the depressurizing means lowers the pressure in the reservoir by discharging the fuel in the reservoir to the outside of the reservoir when one or more of the fuel injection valves is determined as having failed. Namely, the fuel is expelled from the reservoir not only by the failed fuel injection valve but also by the depressurizing means according to this aspect of the invention. Therefore, the fuel remained in the reservoir can be expelled from the reservoir in a short time and, thereby, the abnormal fuel injection from the failed fuel injection valve

ceases in a short time.

According to another aspect of the invention, there is provided a fuel injection system for an internal combustion engine comprising a reservoir for storing pressurized fuel, a fuel injection valve connected to the reservoir and injecting fuel in the reservoir into an internal combustion engine at a predetermined timing, a fuel pump for feeding pressurized fuel to the reservoir at a predetermined timing in order to maintain the pressure of the fuel in the reservoir at a predetermined value and failure determining means for determining whether the fuel injection system has failed, characterized in that the failure determining means comprises pressure detecting means for detecting the pressure of the fuel in the reservoir, fuel injection pressure change detecting means for detecting the actual value of the difference of the pressures in the reservoir before and after the fuel injection from the fuel injection valve based on the pressures detected by the pressure detecting means before and after the fuel injection, fuel injection pressure change estimating means for calculating an estimated value of the difference of the pressures in the reservoir before and after the fuel injection from the fuel injection valve based on a target value of the fuel injection amount and a bulk modulus of elasticity of the fuel, first means for calculating a first characteristic value representing whether the fuel injection system has failed based on the actual value and the estimated value of the difference of the pressures in the reservoir before and after the fuel injection, fuel feed pressure change detecting means for detecting the actual value of the difference of the pressures in the reservoir before and after the fuel feed from the fuel pump based on the pressures detected by the pressure detecting means before and after the fuel feed from the fuel pump, fuel feed pressure change estimating means for calculating an estimated value of the difference of the pressures in the reservoir before and after the fuel feed from the fuel pump based on a target value of the fuel feed amount and the bulk modulus of elasticity of the fuel, and second means for calculating a second characteristic value representing whether the fuel injection system has failed based on the actual value and the estimated value of the difference of the pressures in the reservoir before and after the fuel feed, and that the failure determining means determines whether the fuel injection system has failed based on the first and second characteristic values.

According to this aspect of the invention, the first means calculates the first characteristic value based on the actual value and the estimated value of the difference of the pressures in the reservoir before and after the fuel injection, and the second means calculates the second characteristic value based on the actual value and the estimated value of the difference of the pressures in the reservoir before and after the fuel feed. Namely, the first characteristic value and the second characteristic value are parameters representing whether the fuel injection system has failed. However, the first characteristic value is calculated based on the pressures when the pressure in the reservoir decreasing (i.e., during the fuel injection period) and the second characteristic value is calculated based on the pressures when the pressure in the reservoir increasing (i.e., during the fuel feed period). Therefore, the change in the bulk modulus of elasticity of the fuel affects the first and the second characteristic values in the manner opposite to each other. For example, when the value of the bulk modulus of elasticity becomes larger than the value used for the calculation of the estimated pressures, the value of the first characteristic value increases and the value of the second characteristic value decreases by the amount same as the amount of increase in the first characteristic value. Therefore, by determining the failure of the fuel injection system based on both of the first and the second characteristic values, it becomes possible to eliminate the effect of the bulk modulus of elasticity from the result of the determination.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be better understood from the description as set forth hereinafter, with reference to the accompanying drawings in which:

Fig. 1 schematically illustrates the general configuration of an embodiment of the fuel injection system according to the present invention when it is applied to an automobile engine;
Fig. 2 schematically illustrates the method for detecting the failure of the fuel injection system;
Fig. 3 is a diagram showing typical effects of the change in the bulk modulus of elasticity of fuel on the changes in the pressure in the common rail;
Fig. 4 is a diagram showing typical effects of the pulsation of the pressure in the common rail during the fuel injection;
Fig. 5 is a flowchart explaining an embodiment of the failure determining operation according to the present invention;
Fig. 6 is a diagram explaining the change in the pressure in the common rail when a failure has occurred in the fuel injection system;
Fig. 7 is a flowchart explaining another embodiment of the failure determining operation;
Fig. 8 is a flowchart explaining an embodiment of an operation for correcting the amount of leak from the fuel injection valves;
Fig. 9 is a flowchart explaining an embodiment of an operation for correcting the value of the bulk modulus of elas-

ticity of fuel; and

Figs. 10 through 12 are flowcharts explaining embodiments of the fuel injection control operation when a fuel injection valve has failed.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Hereinafter, embodiments of the present invention will be explained in detail with reference to the accompanying drawings.

Fig. 1 shows a general configuration of an embodiment of the fuel injection system of the present invention when it is applied to an automobile diesel engine.

In Fig. 1, reference numeral 10 designates an internal combustion engine (in this embodiment, a four-cylinder four-cycle diesel engine is used). Numeral 1 designates fuel injection valves which inject fuel into the respective cylinders of the engine 10 and, 3 designates a common rail (a reservoir) to which the fuel injection valves 1 are connected. As explained later, the common rail 3 stores the pressurized fuel fed from a high pressure fuel pump 5 and distributes it to the respective fuel injection valves 1.

In Fig. 1, numeral 7 represents a fuel tank which stores fuel (in this embodiment, diesel fuel) of the engine, and 9 represents a low pressure feed pump which supplies the fuel in the fuel tank 7 to the high pressure fuel pump 5. During the operation of the engine 10, the fuel in the tank 7 is pressurized to a constant pressure by the feed pump 9 and supplied to the high pressure fuel pump 5. Fuel is further pressurized by the high pressure fuel pump 5 and fed to the common rail 3 through a check valve 15 and a high pressure line 17. From the common rail 3, fuel is injected into the respective cylinders through the respective fuel injection valves 1.

Numeral 19 in Fig. 1 shows a fuel return line for returning the fuel from the fuel injection valves 1 to the fuel tank 7. The return fuel from the fuel injection valve will be explained later in detail.

In this embodiment, an electronic control unit (ECU) 20 is provided for controlling the engine 10. The ECU 20 may be constructed as a microcomputer of a known type including a read-only memory (ROM), a random-access memory (RAM), a microprocessor (CPU) and input/output ports all connected to each other by a bi-directional bus. Further, ECU 20 is provided with a backup RAM capable of maintaining its memory contents even if a main switch of the engine is turned off. As explained later, the ECU 20 performs a fuel pressure control which adjusts the fuel pressure in the common rail in accordance with the engine load and speed by controlling the operation of the intake control valve 5a of the high pressure fuel pump 5. Further, the ECU 20 performs a fuel injection control which controls the fuel injection amount by adjusting the opening period of the fuel injection valve 1.

Further, the ECU 20 in this embodiment functions as the failure determining means for determining whether the fuel injection system including the fuel injection valves 1 has failed. The ECU 20 in this embodiment also functions as the depressurizing means for discharging the fuel in the common rail 3 when one or more of the fuel injection valves is determined as having failed.

In order to perform these controls, voltage signals corresponding to the pressure of the fuel in the common rail 3 are supplied to the input port of the ECU 20 from a fuel pressure sensor 31 disposed on the common rail 3 via an AD converter 34. An accelerator signal, which represents the amount of depression of an accelerator pedal by the operator of the automobile, is also supplied to the input port of the ECU 20 via the AD converter 34 from an accelerator sensor 35 disposed near the accelerator pedal (not shown). Further, crank angle signals are supplied from a crank angle sensor 37 to the input port of the ECU 20. In this embodiment, the crank angle sensor 37 is actually composed of two sensors. One is a reference position sensor which is disposed near a camshaft of the engine and generates a reference pulse signal when the crankshaft reaches a reference rotating position (for example, when the first cylinder of the engine 10 reaches the top dead center of the compression stroke), and another is a rotation angle sensor which generates a rotating pulse signal at a predetermined angle of rotation of the crankshaft. These crank angle signals, i.e., the reference pulse signal and the rotating pulse signal are also supplied to the input port of the ECU 20.

The output port of the ECU 20 is connected to the fuel injection valves 1 and a solenoid actuator of the intake control valve 5a of the high pressure fuel pump 5 via respective drive circuits 40 and controls the fuel injection amounts of the fuel injection valves 1 and the fuel feed amount from the high pressure fuel pump 5, respectively.

The high pressure fuel pump 5 in this embodiment is a piston type pump having two cylinders. The pistons of the pump 5 are driven by cams formed on the driving shaft and reciprocate in the respective cylinders. Intake control valves 5a which are opened and closed by the respective solenoid actuators are disposed at the intake ports of the respective cylinders. The driving shaft of the pump 5 in this embodiment is driven by the crankshaft of the engine 10 and rotates synchronously with the crankshaft at one-half the speed thereof. Further, each of the cams formed on the driving shaft has two cam lift portions, thereby the respective cylinders of the pump 5 discharge fuel once per one revolution of the crankshaft. Thus, the pump 5, as a whole, discharges four times per two revolutions of the crankshaft. Since a four-cylinder four-cycle diesel engine is used in this embodiment, the pump 5 is capable of feeding fuel to the common rail 3 at a timing synchronous with the strokes of the respective engine cylinders. For example, the pump 5 in this embodiment

feeds fuel to the common rail at the timing immediately after the fuel injection of the respective cylinders.

Further, the ECU 20 controls the amount of fuel fed from the pump 5 to the common rail 3 by changing the timing where the intake control valve 5a closes during discharge stroke of the pump cylinders. More specifically, the ECU 20 keeps the intake control valve 5a open by de-energizing the solenoid actuator during the inlet stroke and a part of the discharge stroke of the pump cylinder. When the intake control valve 5a is open, the fuel in the pump cylinder flows back to the fuel tank through the intake control valve during the discharge stroke, and fuel is not fed to the common rail 3. When a predetermined time has lapsed from the beginning of the discharge stroke, the ECU 20 closes the intake control valve 5a by energizing the solenoid actuator. By doing so, the fuel trapped in the pump cylinder is pressurized by the piston and, when the pressure in the cylinder exceeds the pressure in the common rail 3, the pressurized fuel in the cylinder pushes open the check valve 15 and flows into the high pressure line 17. Namely, when the intake valve 5a is closed during the discharge stroke of the pump cylinder, fuel is fed to the common rail 3. Once the intake valve 5a is closed, the valve 5a is kept at its closed position during the discharge stroke by the fuel pressure in the pump cylinder regardless of the actuation of the solenoid actuator. Therefore, the amount of the fuel fed to the common rail 3 is determined by the timing at which the intake control valve closes. The ECU 20 in this embodiment controls the fuel feed amount to the common rail 3 by changing the timing for energizing the solenoid actuator of the intake control valve 5a.

In this embodiment, the ECU 20 determines a target value of the common rail pressure based on the engine load (the accelerator signal) and speed. The relationships between the target value of the common rail pressure and the engine load and speed are determined in advance, and stored in the ROM of the ECU 20. Further, the ECU 20 controls the fuel feed amount of the high pressure fuel pump 5 so that the common rail pressure detected by the sensor 31 is kept at the target value. The ECU 20 further calculates the target fuel injection amount from the engine load and speed using a predetermined relationship, and controls the opening period of the fuel injection valves to inject the target amount of fuel from the fuel injection valves.

As explained before, the ECU 20 in this embodiment adjusts the rate of injection of the fuel injection valves 1 in accordance with the operating condition of the engine by changing the common rail pressure, and adjusting the fuel injection amount in accordance with the operating condition of the engine by changing the common rail pressure and opening period of the fuel injection valve. Therefore, the common rail pressure in this embodiment changes in accordance with the operating condition of the engine in a very wide range (for example, from about 10 MPa to about 150 MPa).

Next, the method for detecting the failure of the fuel injection system used in this embodiment is explained.

In this embodiment, the failure of the fuel injection system is determined based on the change in the common rail pressure during the fuel injection period and the change in the common rail pressure during the fuel feed period.

Fig. 2 schematically illustrates the change in the fuel pressure in the common rail 3 during one cycle composed of the fuel injection and the fuel feed period.

In Fig. 2, the period PD represents a period in which fuel injection is performed by one of the fuel injection valves, and the period PU represents a period in which the fuel feed is performed by the fuel pump 5 after each fuel injection. As shown in Fig. 2, the fuel injection from the fuel injection valves 1 and the fuel feed from the fuel pump 5 is performed at different timing so that the fuel injection period PD and the fuel feed period PU do not overlap each other. In Fig. 2, $PC1_0$ represents the pressure in the common rail 3 immediately before the fuel injection (PD) starts, PC2 represents the pressure in the common rail after the fuel injection completes and before the fuel feed (PU) starts. $PC1_1$ represents the pressure in the common rail after the fuel feed completes and before the next fuel injection starts. The interval between the sampling points $PC1_0$ and PC2 is the same as the interval between the sampling points PC2 and $PC1_1$ in this embodiment. In this embodiment, the difference of the common rail pressures before and after the fuel injection (i.e., the change in the pressure during the fuel injection period PD), and the difference of the common rail pressures before and after the fuel feed (i.e., the change in the pressure during the fuel feed period PU), are calculated based on the $PC1_0$, PC2 and $PC1_1$ measured by the fuel pressure sensor 31 by the following formulas.

$$DPC12 = PC2 - PC1_0$$

$$DPC21 = PC1_1 - PC2$$

Where, DPC12 represents the change in the pressure during the fuel injection period PD and takes a negative value, and DPC21 represents the change in the pressure during the fuel feed period PU and takes a positive value. This embodiment further calculates the estimated value DPD of the pressure change during the fuel injection period PD based on the target fuel injection amount, and the estimated value DPU of the pressure change during the fuel feed period PU based on the target fuel feed amount, respectively. The first characteristic value DPDJC and the second characteristic value DPUJC are calculated as the differences between the estimated values (DPD, DPU) and the actual values (DPC12, DPC21), respectively.

Namely, $DPDJC = DPD - DPC12$ and $DPUJC = DPU - DPC21$. The failure of the fuel injection system is deter-

mined based on the first and the second characteristic values DPDJC and DPUJC.

The estimated values of the pressure changes DPD and DPU are calculated by the methods explained below.

The pressure change DPD during the fuel injection period is calculated by the following formula.

$$DPD = -(K/VPC) \times QFINC$$

Where, K is the bulk modulus of elasticity of the fuel, VPC is the volume of the high pressure part of the fuel injection system including the common rail 3, high pressure line 17 and the line connecting the common rail 3 to the fuel injection valves 1. QFINC is a target fuel injection amount expressed in the volume under the reference pressure (for example, 0.1 MPa). The estimated value DPU of the pressure change during the fuel feed period PU is calculated in the similar manner by the following formula.

$$DPU = (K/VPC) \times QPMD$$

QPMD is a target fuel feed amount, i.e., the amount of the fuel flowing into the common rail 3 during the fuel feed period PU. As explained above, the ECU 20 controls the opening period of the fuel injection valves 1 so that the target amount QFINC of the fuel is injected from the fuel injection valve. Therefore, the amount of the fuel actually flowing out from the common rail 3 during the fuel injection period PD becomes the same as QFINC, and the estimated value DPD becomes the same as DPC12, i.e., DPDJC = 0, unless failure occurs in the fuel injection valve or the common rail 3. On the other hand, if a failure, such as a fuel leak, occurs in the fuel injection valve 1 or common rail 3, the actual amount of the fuel flowing out from the common rail 3 becomes larger than QFINC. In this case, the actual change in the common rail pressure DPC12 becomes a negative value larger than the estimated value DPD (i.e., DPC12 < DPD < 0). Therefore, the first characteristic value DPDJC becomes a positive value, and DPDJC becomes larger as the amount of the fuel leak increases.

Considering this fact, in this embodiment, it is provisionally determined that the fuel injection system has failed when the first characteristic value DPDJC is larger than a predetermined reference value R1 (R1 > 0).

Further, since the ECU 20 also controls the intake control valve 5a of the fuel pump 5 so that the target fuel feed amount QPMD of the fuel is actually fed from the pump 5 to the common rail 3, the amount of the fuel flowing into the common rail 3 during the fuel feed period becomes the same as QPMD, and the estimated value DPU becomes the same as the actual value DPC21, i.e., DPUJC = 0, unless a failure occurs in the fuel pump 5 or the common rail 3. However, if a leak from the common rail 3 or the sticking of the fuel injection valve at the opening position occurs, the amount of the fuel actually supplied to the common rail 3 becomes less than QPMD, and the actual pressure change DPC21 becomes smaller than the estimated pressure change DPU (i.e., 0 < DPC12 < DPU). Therefore, the second characteristic value DPUJC becomes a positive value, and the DPUJC becomes larger as the amount of the fuel leak increases.

Considering this fact, it is also provisionally determined in this embodiment that the fuel injection system has failed when the second characteristic value DPUJC is larger than a predetermined reference value R2 (R2 > 0).

As explained above, since both of the first and the second characteristic values DPDJC and DPUJC become.larger than the reference values when a fuel leak occurs in the system, it may be considered that the failure of the system can be determined correctly by using one of the characteristic values only, i.e., it is not necessary to use both the characteristic values to determine the failure. However, when the pressure in the common rail changes in a wide range, the value of the bulk modulus of elasticity K of the fuel also changes in a wide range. When the value of the bulk modulus of elasticity varies largely, it is difficult to determine the failure of the system based only one of the characteristic values. This problem is illustrated in Fig. 3.

Fig. 3 is a diagram similar to Fig. 2 which illustrates the pressure changes in the common rail when the value of the bulk modulus of elasticity changes. In Fig. 3, the solid line I represents the pressure change where the actual value of the bulk modulus of elasticity k agrees with the value used for calculating the estimated pressure changes DPD and DPU. In this case, if the fuel leak from the system does not exist, the estimated values DPD and DPU calculated by the formulas explained before agree with the actual pressure changes (DPC120 and DPU210 in Fig. 3), respectively, and both the first characteristic DPDJC and the second characteristic value DPUJC become 0.

On the other hand, if the value of the bulk modulus of elasticity K changes due to the change in the pressure of the fuel, the actual pressure change in the common rail becomes as indicated by the broken lines II or III in Fig. 3. The broken line II and III show the cases where the value of the bulk modulus of elasticity increases (the line II) and decreases (the line III), respectively, while the fuel injection amount and the fuel feed amount are maintained at the same as the case represented by the solid line I.

As seen from Fig. 3, when the value of the bulk modulus of elasticity K increases (line II), the actual pressure change during the fuel injection period becomes a negative value (DPC12L) larger than the same (DPC120) in the case of line I (i.e., DPC12L < DPC120 < 0), and the pressure change during the fuel feed period becomes a positive value (DPC21L) larger than the same (DPC210) in the case of line I (i.e., 0 < DPC210 < DPC21L). In this case, if the fuel leak

does not exist, the estimated value DPD becomes the same as DPC120 in Fig. 3. Therefore, if the value of the bulk modulus of elasticity K becomes larger than the value used for the calculation of DPD due to the change in the pressure, the first characteristic value DPDJC (= DPD - DPC12L) becomes a positive value even though the fuel leak does not exist. Thus, the first characteristic value DPDJC may become larger than the reference value R1 when the change in the value of the bulk modulus of elasticity K is large. In this case, if the failure of the fuel injection system is determined, based only on the first characteristic value DPDJC, the system is incorrectly determined as having failed even though a fuel leak does not exist.

Similarly, when the value of the bulk modulus of elasticity K decreases (line III in Fig. 3), both the pressure changes during the fuel injection period and the fuel feed period becomes a negative value (DPC12S) smaller than DPC210 in the case of line I, and a positive value (DPC21S) smaller than DPC210, respectively. In this case, if the fuel leak does not exist, the estimated value DPU becomes the same as DPC210 in Fig. 3. Therefore, when the value of the bulk modulus of elasticity K becomes smaller than the value used for calculating DPU, the second characteristic value DPUJC (= DPU - DPC21) becomes a positive value even though the fuel leak does not exist. Therefore, if the failure of the fuel injection system is determined, based only on the second characteristic value DPUJC, DPUJC may become larger than the reference value R2 when the change in the value of the bulk modulus of elasticity K is large, and the system is incorrectly determined as having failed even though a fuel leak does not exist.

In order to prevent this problem, both of the failure determination based on the first characteristic value DPDJC and the failure determination based on the second characteristic value DPUJC are always performed, and the fuel injection system is determined as having failed only when both the determination results indicate that the system has failed.

As explained above, the first characteristic DPDJC becomes a positive value even though the fuel injection system is normal when the value of the bulk modulus of elasticity K increases since the actual value DPC12 becomes a negative value (DPC12L) larger than the estimated value DPD. In this case, however, the actual value of the pressure change during the fuel feed period DPC21 also becomes a positive value (DPC21L) larger than the estimated value DPU. Therefore, in this case, the second characteristic value DPUJC (= DPU - DPC21) always becomes a negative value. Namely, when the value of the bulk modulus of elasticity K increases, though the first characteristic value DPDJC increases, the second characteristic value DPUJC decreases if the fuel injection system is normal. Therefore, even if the first characteristic value DPDJC becomes larger than the reference value R1 due to an increase in the value of the bulk modulus of elasticity K, the second characteristic value DPUJC decreases and always becomes smaller than the reference value R2, provided the fuel injection system is normal.

Similarly, when the value of the bulk modulus of elasticity K decreases due to the change in the pressure, though the second characteristic value becomes a positive value, the first characteristic value always becomes a negative value since the actual pressure change DPC12 becomes a negative value (DPC12S) smaller than the estimated value DPD, provided the fuel injection system is normal. In this case, the first characteristic value DPDJC always becomes smaller than R1 even if the second characteristic value DPUJC becomes larger than R2.

This means that, if the fuel injection system has not failed, at least one of the determinations based on the first characteristic value DPDJC and on the second characteristic value DPUJC always determine that the fuel injection system has not failed determines that the fuel injection system is normal, even when the value of the bulk modulus of elasticity K changes from the value used for the calculations of the estimated values DPD and DPU. In other words, it can be considered that the failure, such as a leak from the fuel injection valve, has actually occurred in the fuel injection system if both of the determination results based on DPDJC and DPUJC indicates that the system has failed. Therefore, in this embodiment, the failure of the system is provisionally determined by both of the methods based on the first and the second characteristic values DPDJC and DPUJC and only when the results of both provisional determination indicate that the system has failed, it is determined that the fuel injection system has actually failed. By determining the failure based on the results of both provisional determinations, the error in the determination due to change in the value of bulk modulus of elasticity can be eliminated.

Further, the above is also effective to eliminate the error in the determination caused by the pulsation in the pressure in the common rail. Fig. 4 is a diagram similar to Fig. 2 which illustrates the case where the pressure in the common rail pulsates. In Fig. 4, the pressure in the common rail becomes lower than the actual value at the timing where PC2 should be measured due to the pulsation of the pressure in the common rail. If this type of the pulsation exists, the measured pressure change DPC12 (= PC2 - $PC1_0$) becomes a negative value larger than the true pressure change (DPC120 in Fig. 4), and the first characteristic value DPDJC (= DPD - DPC12) becomes a positive value. Therefore, if the pulsation is large, the first characteristic value DPDJC may become larger than the reference value R1 even though the fuel injection system has not failed. However, even in this case, the measured pressure change DPC21 (= $PC1_1$ - PC2) always becomes a positive value larger than the true pressure change (DPC210 in Fig. 4), and the second characteristic value DPUJC (= DPU - DPC21) always becomes smaller than the reference value R2. Similarly, if the measured PC2 becomes higher than the true value due to the pulsation, though the second characteristic value DPUJC may becomes larger than the reference value R2, the first characteristic value DPDJC always become smaller than the reference value R1 if the system has not failed.

Therefore, it can be also considered, in this case, that the fuel injection system has actually failed only when both the results of the determinations based on the first and the second characteristic values indicate that the system has failed even though the pressure pulsation exists in the common rail.

Fig. 5 is a flowchart illustrating the failure determining operation according to this embodiment. This operation is carried out as a routine executed by the ECU 20, for example, at predetermined rotation angles of the crankshaft of the engine.

In Fig. 5, at step 501, the ECU 20 reads the pressure PC in the common rail 3 and the crank rotation angle CA from the fuel pressure sensor 31 and the crank angle sensor 37, respectively. At steps 503 through 511, the ECU 20 further determines whether the present crank angle CA read in at step 501 agrees with any of predetermined values $CA1_0$ (step 503), CA2 (step 507) and $CA1_1$ (step 511) and, if CA agrees none of $CA1_0$, CA2 and $CA1_1$, the operation terminates immediately after step 511. The crank angle $CA1_0$ corresponds to the timing immediately before the start of the fuel injection in the respective cylinder, i.e., the sampling timing of the pressure $PC1_0$ in Fig. 2. The crank angle CA2 corresponds to the timing immediately before the start of the fuel feed in the respective cylinder and corresponds to the sampling timing of the pressure PC2 in Fig. 2. Further, the crank angle $CA1_1$ corresponds to the timing immediately after the completion of the fuel feed and corresponds to the sampling timing of the pressure $PC1_1$ in Fig. 2.

If the present crank angle CA agrees with the sampling timing of $PC1_0$ (i.e., $CA = CA1_0$) at step 503, the ECU 20 stores the present values of the pressure PC as $PC1_0$ (step 505) and, if the present crank angle CA agrees with the sampling timing of PC2 (i.e., CA = CA2) at step 507, the ECU 20 stores the present value of PC as PC2 at step 509. If CA = CA 11 at step 511, i.e., if the present crank angle CA agrees with the sampling timing of $PC1_1$ at step 511, the value of PC is stored as $PC1_1$ at step 513.

When the value of $PC1_1$ is stored at step 513, the actual values of the pressure changes during the fuel injection period and the fuel feed period (DPC12 and DPC21) are calculated at step 515 by $DPC12 = PC2 - PC1_0$, and by $DPC21 = PC1_1 - PC2$. Further, at step 517, the estimated values of the pressure changes during the fuel injection period and the fuel feed period (DPD and DPU) are calculated by $DPD = -(K/VPC) \times QFINC$ and, by $DPU = (K/VPC) \times QPMD$ using a predetermined value of the bulk modulus of elasticity K of the fuel (a constant value), the target value of the fuel injection amount QFINC and the target value of the fuel feed amount QPMD. The target value for the fuel injection amount QFINC and the target value for the fuel feed amount QPMD are calculated by the fuel injection amount calculation routine and the fuel feed amount calculation routine (not shown), respectively, performed separately by the ECU 20 based on the engine load (accelerator signal) and the engine speed.

At step 519, the first and the second characteristic values DPDJC and DPUJC are calculated by $DPDJC = DPD - DPC12$ and $DPUJC = DPU - DPC21$.

At steps 521 and 523, the provisional determination of the failure is performed by comparing DPDJC with the predetermined reference value R1, and DPUJC with another predetermined reference value R2. In this embodiment, the value of a failure flag XD is set to either 1 (failed) or 0 (normal) in accordance with the results of both the provisional determinations carried out at steps 521 and 523. Namely, the value of the flag XD is set to 1 (failed) at step 525 only when $DPDJC > R1$ and $DPUJC > R2$, and if either $DPDJC \leq R1$ or $DPUJC \leq R2$, the value of the flag XD is set to 0 (normal) at step 527.

When the value of the failure flag XD is set to 1, an alarm is activated in this embodiment, in order to notify the driver of the automobile that the fuel injection system has failed. The value of the flag XD may be stored in the backup RAM of the ECU 20 to prepare for future inspection and maintenance.

Next, another embodiment of the failure determining operation is explained with reference to Figs. 6 and 7. Fig. 6 is a diagram similar to Fig. 2, but illustrates the case where the value of the bulk modulus of elasticity K does not change from the value used for calculating DPD and DPU. In Fig. 6, the solid line I shows the pressure change in the common rail where the fuel leak has occurred, and the broken line II shows the pressure change where the fuel leak does not exist. As seen from Fig. 6, line I, the pressure drop during the fuel injection period increases by an amount b due to the fuel leak compared to the line II, i.e., the pressure after the fuel injection period PC2 decreases by the amount b due to the fuel leak. Further, since the fuel leak also exists during the fuel feed period, the pressure rise during the fuel feed period decreases by the amount b and the pressure $PC1_1$ after the fuel feed becomes low compared to the line II by the amount 2b. However, the estimated values of the pressure changes DPD and DPU are the same for line I and line II since the bulk modulus of elasticity K does not change.

In this case, both the first characteristic value DPDJC and the second characteristic value DPUJC become equal to b ($b > 0$) as seen from Fig. 6.

Namely, $DPDJC = DPD - DPC12 = b$, and $DPUJC = DPU - DPC21 = b$.

On the other hand, as shown in Fig. 3, if the PC2 decreases by an amount a in the conditions where the bulk modulus of elasticity K increases and where the fuel leak does not exist (the broken line II in Fig. 3), the pressure drop DPC12 during the fuel injection period and the pressure rise DPC21 during the fuel feed period both increases. In this case, the first characteristic value DPDJC and the second characteristic value DPUJC become as follows.

$$DPDJC = DPD - DPC12L = DPC120 - DPC12L = a$$

$$DPUJC = DPU - DPC21L = DPC210 - DPC21L = -a$$

(a > 0)

Therefore, if the change in the bulk modulus of elasticity K (Fig. 3) and the fuel leak (Fig. 6) occurs at the same time, the changes in the first and the second characteristic values are expressed by the following formulas.

$$DPDJC = a + b$$

$$DPUJC = -a + b$$

In the above formulas, the amounts a and -a represents the effect of the change in the bulk modulus of elasticity K and the amount b represents the effect of the fuel leak.

As is understood from the above formulas, the magnitude of the changes in the first and the second characteristic values (a and -a) due to the change in the bulk modulus of elasticity K are always the same amount but with opposite signs. Therefore, by adding DPDJC and DPUJC, the effect of the change in the bulk modulus of elasticity K on the first and the second characteristic values cancel each other. This means that the sum of the first characteristic value and the second characteristic value represents only the effect of the fuel leak. Therefore, if the value of the sum DPDJC + DPUJC = 2b (b represents the amounts of changes in the first and the second characteristic values) increases to some extent, it can be determined, regardless of the change in the value of the bulk modulus of elasticity K, that a fuel leak has occurred in the fuel injection system.

Considering the above, this embodiment determines that the failure of the fuel injection system (i.e., the fuel leak) has occurred when the sum of the first and the second characteristic values becomes a predetermined reference value R3 (DPDJC + DPUJC > R3, R3 is, for example, R1 + R2).

Fig. 7 is a flowchart illustrating the failure determining operation as explained above. This operation is carried out as a routine performed by the ECU 20, for example, at predetermined rotation angles of the crankshaft.

In Fig. 7, steps 701 through 719 are steps for calculating the first characteristic value DPDJC and the second characteristic value DPUJC. Steps 701 through 709 are substantially the same as steps 501 through 519 in Fig. 5, and the detailed explanation is omitted.

When DPDJC and DPUJC are calculated by the steps 701 through 719, the value JC of the sum of DPDJC and DPUJC is obtained by JC = DPDJC + DPUJC at step 721.

At step 723, it is determined whether the calculated value of JC is larger than a predetermined value R3, and if JC > R3, the value of the failure flag XD is set to 1 (failed) at step 725. If JC > R3 at step 723, the value of the failure flag XD is set to 0 (normal) at step 727. When the value of the failure flag XD is set to 1, an alarm is activated also in this embodiment, and the value of the flag XD may be stored in the backup RAM of the ECU 20 to prepare for future inspection and maintenance.

As explained above, the failure of the fuel injection system can be determined correctly by the failure determining operation in Fig. 7, regardless of the change in the value of the bulk modulus of elasticity K.

Though the effect of the change in the bulk modulus of elasticity of fuel K is cancelled by adding the first and the second characteristic values in the embodiment of Fig. 7, also it is possible to calculate the actual value of the bulk modulus of elasticity K and the actual amount of a normal fuel leak based on the first and the second characteristic values. If the actual values of the amount of the normal fuel leak and the bulk modulus of elasticity K of the fuel is taken into consideration when calculating the estimated values DPD and DPU, the accuracy of the estimated values are largely improved.

First, the normal fuel leak from the fuel injection valves is explained. It is assumed that only the fuel injected from the fuel injection valves flows out from the common rail when the fuel injection system is normal. However, a small amount of fuel always leaks from the clearances of the sliding parts of the fuel injection valves and is returned to the fuel tank 7 through the fuel return line 19 even if the fuel injection system is normal. If the amount of this normal fuel leak is incorporated into the calculation of the estimated values DPD and DPU, the accuracy of the estimated values is further improved. However, since the clearances in the sliding parts change depending on the operation hours of the engine, the amount of the normal fuel leak also changes depending on the operation hours of the engine. Therefore, it is necessary to estimate the actual amount of the normal fuel leak during the engine operation in order to improve the accuracy of the estimated values DPD and DPU.

As explained before, the change in the common rail pressure becomes as illustrated by the solid line I in Fig. 6 when the fuel leak from the common rail exists. When the normal fuel leak exists, the pressure change in the common rail also becomes as illustrated by the solid line I in Fig. 6. Therefore, the difference between the estimated pressures and the actual pressures (indicated by the amount b in Fig. 6) corresponds to the amount of the normal fuel leak if the

fuel injection valves are normal. In this embodiment, the amount b is calculated from the first and the second characteristic values when it is confirmed by other methods that the fuel injection valves are normal. Since the amount b directly corresponds to the amount of the normal fuel leak in this condition, the amount of the fuel leak used in the calculations is corrected based on the amount b in this embodiment.

When the normal fuel leak amount during the fuel injection period (PD in Fig. 2) is represented by QL, the estimated value DPD of the pressure change during the fuel injection period is expressed by the following formula, provided no other fuel leak exists.

$$DPD = -(K/VPC) \times (QFINC + QL)$$

Further, if the normal fuel leak amount has changed from QL to (QL + ΔQ) during the engine operation, i.e., if there is the difference ΔQ between the actual value of the normal fuel leak and the value used for the calculation of DPD, the actual value DPC12 of the pressure change during the fuel injection period is expressed by the following formula.

$$DPC12 = -(K/VPC) \times (QFINC + QL + \Delta Q)$$

Therefore, if the difference of b in the values DPD and DPC12 is caused only by the change ΔQ in the normal fuel leak amount, the amount of the change ΔQ can be calculated from the difference b.

Namely, since $DPD - DPC12 = b$ as shown in Fig. 6, $(K/VPC) \times \Delta Q = b$ is obtained from the above-explained formulas. Therefore, the value of ΔQ is calculated by $\Delta Q = b \times (VPC/K)$.

Further, as explained before, if the fuel injection system is normal, the sum of the first characteristic value DPDJC and the second characteristic value DPUJC always becomes 2b (i.e., $DPDJC + DPUJC = 2b$) irrespective of the change in the bulk modulus of elasticity K of the fuel and the pulsation of the pressure in the common rail. Therefore, in this embodiment, the first and the second characteristic values are calculated when it is confirmed that the fuel injection system is normal, and the amount of the normal fuel leak used for the calculations of the estimated values DPDJC and DPUJC is corrected based on the sum of the first characteristic value and the second characteristic value.

Fig. 8 is a flowchart illustrating the correcting operation of the normal fuel leak amount as explained above. This operation is carried out as a routine performed by the ECU 20 at predetermined intervals.

When the operation starts in Fig. 8, at step 801, the ECU 20 determines whether the fuel injection system is normal based on the value of the failure flag XD. The value of the failure flag is set to either 0 (normal) or 1 (failed) in the failure determining operation, for example, in Figs. 5 or 7, separately performed by the ECU 20. If XD = 1, i.e., if it is determined that the fuel injection system has failed, the operation terminates without executing step 803 to 809. If the system is normal (XD ≠ 1 at step 801), i.e., if no fuel leak other than the normal fuel leak exists, the ECU 20 performs step 803 in order to calculate the first characteristic value DPDJC and the second characteristic value DPUJC. DPDJC and DPUJC are calculated in a manner similar to steps 501 through 519 in Fig. 5. However, at step 803, the estimated values of the pressure change DPD and DPU are calculated in consideration of the normal fuel leak amount QL by the following formula.

$$DPD = -(K/VPC) \times (QFINC + QL)$$

$$DPU = (K/VPC) \times (QPMD - QL)$$

At step 805, the amount b is calculated from DPDJC and DPUJC by $b = (1/2) \times (DPDJC + DPUJC)$.

Further, the change ΔQ in the normal fuel leak amount QL is calculated at step 807 by $\Delta Q = b \times (VPC/K)$.

The calculated ΔQ is used for correcting the normal fuel leak amount QL at step 807, and the amount (QL + ΔQ) is stored as the corrected value of the normal fuel leak amount.

By performing the operation in Fig. 8 periodically, the normal fuel leak amount QL used for calculating the estimated pressure changes DPD and DPU always becomes the same as the actual normal fuel leak amount irrespective of the change in the clearances of the sliding parts in the fuel injection valves. Therefore, the accuracy of the failure determination is further improved.

Next, the correction of the bulk modulus of elasticity K of the fuel is explained.

Consider the case where no fuel leak other than the normal fuel leak exists in the system and where the value of the normal fuel leak amount QL used for calculating DPD and DPU agrees with the actual normal fuel leak amount. In this case, if the actual value of the bulk modulus of elasticity increases from the value K used for calculating DPD and DPU by the amount ΔK, the values of the actual pressure change DPC12 and the estimated pressure change DPD are expressed by the following formula.

$$DPC12 = -\{(K + \Delta K)/VPC\} \times (QFINC + QL)$$

$$DPD = -(K/VPC) \times (QFINC + QL)$$

If the difference between DPD and DPC12 is a as shown in fig 3, i.e., if DPD - DPC12 = a (=DPDJC) , the amount of the change ΔK in the bulk modulus of elasticity K is calculated by the following formula.

$$\Delta K = a \times \{VPC/(QFINC + QL)\}$$

Further, if the fuel leak other than the normal fuel leak exists, the value of DPC12 further changes by the amount b (Fig. 6). Therefore, in this case, the difference between DPD and DPC12, i.e. the value of DPDJC becomes (a + b). Similarly, the value of DPUJC becomes (-a + b) in this case.

Namely, DPDJC = a + b , and DPUJC = -a + b .

Therefore, the amount of the difference a due to the change in the bulk modulus of elasticity can be obtained by the following formula.

$$a = (DPDJC - DPUJC)/2$$

The amount of the change ΔK of the bulk modulus of elasticity K is calculated using this value a by $\Delta K = a \times \{VPC/(QFINC + QL)\}$.

Fig. 9 is a flowchart illustrating the correcting operation of the bulk modulus of elasticity. This operation is carried out as a routine performed by the ECU 20 at predetermined intervals.

In Fig. 9, at step 901, the first and the second characteristic values DPDJC and DPUJC are calculated in the manner same as step 803 in Fig. 8.

At step 903, the amount of difference a is calculated based on DPDJC and DPUJC by a = (DPDJC - DPUJC)/2 and, at step 905, the change ΔK in the bulk modulus of elasticity is calculated by $\Delta K = a \times \{VPC/(QFINC + QL)\}$.

Further, at step 907, the bulk modulus of elasticity k used for calculating DPD and DPU at step 901 is corrected using the calculated ΔK, and the value $(K + \Delta K)$ is stored as the new bulk modulus of elasticity K of the fuel.

By performing the operation in Fig. 9, the bulk modulus of elasticity K used for calculating the estimated pressure change DPD and DPU is always agrees with the actual value. Therefore, the failure of the fuel injection system is accurately determined irrespective of the change in the bulk modulus of elasticity of the fuel.

Next, another embodiment of the present invention is explained. In the previous embodiments, the failure of the fuel injection system such as the failure in the fuel injection valves is detected. However, when the failure of the fuel injection valve, for example, an abnormal fuel injection due to the sticking of the fuel injection valve at its opening position occurs, the maximum cylinder pressure may excessively increase as explained before. In this embodiment, the pressure in the common rail is lowered in a short time when the failure of the system is detected, in order to terminate the fuel injection from the failed fuel injection valve in a short time.

In this embodiment, when the fuel injection system is determined as having failed by the failure detecting operation, the solenoid actuator of the intake control valve 5a of the high pressure fuel pump 5 is de-energized in order to keep the intake control valve 5a open. By opening the intake control valve 5a, the fuel feed from the high pressure fuel pump 5 to the common rail 3 is stopped. However, though fuel is not supplied to the common rail 3 in this condition, a large amount of fuel remains in the common rail 3 due to a high fuel pressure in the common rail. Therefore, if the engine is stopped in this condition, though the fuel injection from the fuel injection valves not having failed is stopped, the fuel remained in the common rail may continue to flow into the cylinder through the failed fuel injection valve. Since a diesel engine is used in this embodiment, the combustion in the cylinder continues due to the fuel supplied through the failed fuel injection valve, and the abnormal combustion and the resulting excessively high maximum cylinder pressure continues for a long time until all the fuel remained in the common rail is discharged through the failed fuel injection valve.

In this embodiment, therefore, the fuel injection from the fuel injection valves not being failed is continued even when the failure of the fuel injection valve is detected. Namely, in this embodiment, the fuel injection from all the fuel injection valves including the failed fuel injection valve is continued. Therefore, the fuel remained in the common rail 3 is discharged from the common rail through all of the fuel injection valves, thereby the pressure in the common rail can be lowered rapidly in order to stop the abnormal fuel injection from the failed fuel injection valve in a short time. Thus, the period in which the engine is exposed to the excessively high maximum cylinder pressure can be shortened.

Fig. 10 is a flowchart illustrating the fuel injection control operation when the failure of the fuel injection valve is detected. This control operation is carried out as a routine performed by the ECU 20 at predetermined intervals.

In Fig. 10, at step 1001, it is determined whether any of the fuel injection valves has failed. In this embodiment, the failure of the fuel injection valve may be determined by one of the failure determining operations explained above. However, other method for determining the failure of the fuel injection valves can be also used in this embodiment.

For example, the failure of the fuel injection valves can be detected by measuring the actual pressure drop in the common rail during the fuel injection period of the respective fuel injection valves. If the amount of the actual pressure

drop during the fuel injection period of a particular fuel injection valve deviates from the pressure drops of the other fuel injection valves, it can be determined that a failure, such as sticking of the fuel injection valve, has occurred in the fuel injection valve in question.

Alternatively, the failure of the fuel injection valves can be detected from the fluctuation of the rotating speed of the crankshaft. Since the output torque of the cylinder increases due to an increase in the maximum cylinder pressure if the abnormal fuel injection occurs, it can be determined that the fuel injection valve of the cylinder has failed when the rotating speed of the crankshaft, during the combustion stroke of the cylinder, becomes larger than the same of other cylinders.

Further, the failure of the fuel injection valve can be detected from the air-fuel ratio of the exhaust gas of the engine. When the abnormal fuel injection occurs in the cylinder, the air-fuel ratio of the exhaust gas from the cylinder becomes lower due to increase in the amount of the fuel supplied to the cylinder. Therefore, if the engine is equipped with an air-fuel ratio sensor in the exhaust gas passage for detecting the air-fuel ratio of the exhaust gas, the amount of the fuel supplied to the respective cylinders can be calculated from the output of the air-fuel ratio sensor and the timing at which the exhaust gases from the respective cylinders reach the air-fuel ratio sensor. Thus, it can be determined that the abnormal fuel injection has occurred in the cylinder when the amount of the fuel supplied to the cylinder becomes larger than the amount of the fuel supplied to the other cylinders.

In this embodiment, one or more of the methods explained above is used for detecting the failure of the fuel injection valves at step 1001 in Fig. 10.

If the failure (the abnormal fuel injection) is detected at step 1001, the ECU 20 de-energizes the solenoid actuator of the intake control valve 5a of the high pressure fuel pump 5 in order to stop the fuel feed to the common rail 3. Further, the ECU 20 continues the fuel injection of all the fuel injection valves of the engine including the failed fuel injection valve at step 1005. Therefore, the fuel remained in the common rail 3 is distributed to all the cylinders of the engine, i.e., the remained fuel is discharged from the common rail not only from the failed fuel injection valve but from all of the fuel injection valves. Thus, the pressure in the common rail decreases rapidly and the fuel injection from the failed fuel injection valve terminates in a short time.

If the common rail 3 is connected to the fuel return line 19 via a solenoid operated shut off valve, it is also possible to discharge the remained fuel from the common rail to the fuel return line 19 by opening the shut off valve. However, according to the embodiment in Fig. 10, the common rail can be depressurized in a short time without requiring the solenoid operated shut off valve.

Next, another embodiment of the present invention is explained with reference to Fig. 11. In this embodiment, the fuel injection from the normal fuel injection valves is also continued when the failure of the fuel injection valve is detected as explained in the embodiment of Fig. 10. However, in addition to that, the fuel injection amount from the normal fuel injection valves is increased when the failure is detected, compared to the fuel injection amount before the failure is detected. As explained before, the ECU 20 calculates the target fuel injection amount based on the engine load (the accelerator signal) and the engine speed, and controls the respective fuel injection valves so that the fuel injection amounts from the respective fuel injection valves agree with the target fuel injection amount. In the embodiment in Fig. 10, though the fuel injection from the normal fuel injection valves is continued when the failure is detected, the fuel injection amounts from the normal fuel injection valves are maintained at the target value. In contrast to this, in this embodiment, the fuel injection amount of the normal fuel injection valves is controlled at a value larger than the target fuel injection amount when the failure is detected. By increasing the fuel injection amount of the normal fuel injection valves, the rate of the fuel discharged from the common rail becomes larger than the rate in the embodiment in Fig. 10 and, thereby, the time required for decreasing the pressure in the common rail is further shortened. When the fuel injection amount is increased, the maximum cylinder pressure and the output torque of the cylinder also increase in the cylinders connected to the normal fuel injection valves. Therefore, the amount of increase of the fuel injection amount is determined in such a manner the increases in the maximum cylinder pressure and the output torque of the cylinders connected to the normal fuel injection valves are maintained within the allowable limits in this embodiment.

Fig. 11 is a flowchart illustrating the fuel injection control operation as explained above. This control operation is carried out as a routine performed by the ECU 20 at predetermined intervals.

In Fig. 11, at step 1101, it is determined whether any of the fuel injection valves has failed. At step 1101, the failure of the fuel injection valve is determined using the same method as step 1001 in Fig. 10. If the failure in any fuel injection valve is detected at step 1101, the ECU 20 also stops the fuel feed from the high pressure fuel pump 5 to the common rail 3 by de-energizing the solenoid actuator of the intake control valve 5a. Further, in this embodiment, the ECU 20 identifies the failed fuel injection valve at step 1105, and sets the value of a fuel increment flag XI to 1 at step 1107. When the fuel increment flag XI is set to 1, the target fuel injection amount calculated by another routine is increased at a predetermined ratio for the fuel injection valves other than the failed fuel injection valve. If failure is not detected in any of the fuel injection valves at step 1101, the ECU 20 sets the value of the fuel increment flag to 0 at step 1109. In this case, the target fuel injection amount is maintained at the value in the normal operation.

Next, another embodiment of the present invention is explained with reference to Fig. 12.

In the embodiment of Fig. 11, the fuel injection amounts of the normal fuel injection valves are increased when the failure is detected. However, as explained before, the amount of increase must be restricted within the allowable limit of the increases in the maximum cylinder pressure and the output torque of the cylinders. Therefore, in some cases, the fuel injection amounts of the normal fuel injection valves cannot be increased sufficiently. Therefore, the time required for depressurizing the common rail is not sufficiently shortened in some cases. In this embodiment, therefore, the fuel injection timing of the normal fuel injection valves is delayed in order to lower the maximum cylinder pressure and the output torque of the cylinders connected to the normal fuel injection valves when the failure is detected. As is well known, when the fuel injection timing is delayed, the start of the combustion in the cylinder is also delayed to the latter part of the combustion stroke, and the maximum cylinder pressure becomes lower since the exhaust valve opens before the cylinder pressure reaches the maximum pressure. Further, if the fuel injection timing is delayed until the exhaust stroke of the cylinder, the combustion does not occur in the cylinder. Therefore, by delaying the fuel injection timing, the fuel injection amount can be largely increased without increasing the maximum cylinder pressure and the output torque. In this embodiment, the fuel injection amount is increased largely and, at the same time, the fuel injection timing is delayed in the normal fuel injection valves in order to depressurize the common rail in a very short time without increasing the maximum cylinder pressure and the output torque of the cylinders.

Fig. 12 is a flowchart illustrating the fuel injection control operation when the failure of the fuel injection valve is detected. This control operation is carried out as a routine performed by the ECU 20 at predetermined intervals.

In Fig. 12, at step 1201, it is determined whether any of the fuel injection valves has failed. At step 1201, the failure of the fuel injection valve is determined using the same method as step 1001 in Fig. 10. If the failure in any fuel injection valve is detected at step 1201, the ECU 20 also stops the fuel feed from the high pressure fuel pump 5 to the common rail 3 by de-energizing the solenoid actuator of the intake control valve 5a. Further, the ECU 20 identifies the failed fuel injection valve at step 1205, and sets the value of a fuel increment flag XI to 1 at step 1207. When the fuel increment flag XI is set to 1, the target fuel injection amount calculated by another routine is increased at a predetermined ratio for the fuel injection valves other than the failed fuel injection valve. However, the amount of increase in the fuel injection amount in this embodiment is set at an amount larger than the same in the embodiment of Fig. 11. Further, at step 1209, the ECU 20 sets the value of the delay flag XR to 1.

When the value of the delay flag XR is set to 1, the fuel injection timing of the fuel injection valves including the failed fuel injection valve is delayed, for example, until the exhaust stroke of the respective cylinders. Therefore, the fuel injected from the normal fuel injection valves is discharged from the cylinders without burning and, thereby, the excessive increase in the maximum cylinder pressure and the output torque does not occur even if the fuel injection amount is largely increased.

If it is determined that all of the fuel injection valves are normal, the values of the flags XI and XR are both set to 0 at steps 1211 and 1213, respectively and, in this case, the fuel injection from the fuel injection valves are performed normally.

The time required for depressurizing the common rail varies in accordance with the types of the engine and the pressure in the common rail. However, it was found through experiment that approximately ten fuel injection cycles of the respective cylinders are required to depressurize the common rail (i.e., to terminates the abnormal fuel injection) in a typical case if the fuel injection from the normal fuel injection valves are stopped when the abnormal fuel injection from one fuel injection valve occurs. The required number of fuel injection cycles is reduced to about five cycles if the normal fuel injection valves continue the fuel injection when the abnormal fuel injection occurs. Further, if the fuel injection amounts of the normal fuel injection valves are increased without delaying the fuel injection timing, the number of cycles required for depressurizing is further reduced to three to four cycles. However, it is found that the common rail can be depressurized in one or two fuel injection cycles of the respective cylinders, if the fuel injection amount is largely increased by delaying the fuel injection timing.

Claims

1. A fuel injection system for an internal combustion engine comprising a reservoir (3) for storing pressurized fuel, fuel injection valves (1) connected to the reservoir (3) and injecting fuel in the reservoir into an internal combustion engine (1) at a predetermined timing, a fuel pump (5) for feeding pressurized fuel to the reservoir (3) at a predetermined timing in order to maintain the pressure of the fuel in the reservoir at a predetermined value and failure determining means (20) for determining, for each of the fuel injection valves (1), whether it has failed, characterized in that said fuel injection system further comprises:

   fuel feed cut means (20) for stopping the fuel feed to the reservoir (3) from the fuel pump (5) when said failure determining means (20) determines that any of the fuel injection valves (1) has failed; and
   depressurizing means (20) for discharging the fuel in the reservoir (3) to the outside of the reservoir when said failure determining means (20) determines that any of the fuel injection valves (1) has failed.

2. A fuel injection system as set forth in claim 1, wherein said depressurizing means (20) discharges the fuel to the outside of the reservoir (3) by injecting fuel from all of the fuel injection valves (1) including the fuel injection valve determined as being failed.

3. A fuel injection system as set forth in claim 2, wherein said depressurizing means (20) further increases the fuel injection amounts of the fuel injection valves (1) other than the fuel injection valve determined as being failed compared to the fuel injection amounts before the fuel injection valve is determined as being failed.

4. A fuel injection system as set forth in one of the claims 2 and 3, wherein said depressurizing means (20) further comprises injection retarding means (20) for delaying the timing of the fuel injection of the fuel injection valves (1) at least other than the fuel injection valve determined as being failed from the fuel injection timing before the fuel injection valve is determined as being failed.

5. A fuel injection system for an internal combustion engine comprising a reservoir (3) for storing pressurized fuel, a fuel injection valve (1) connected to the reservoir and injecting fuel in the reservoir (3) into an internal combustion engine (10) at a predetermined timing, a fuel pump (5) for feeding pressurized fuel to the reservoir (3) at a predetermined timing in order to maintain the pressure of the fuel in the reservoir (3) at a predetermined value and failure determining means (20) for determining whether the fuel injection system has failed, characterized in that said failure determining means comprises:

pressure detecting means (31) for detecting the pressure of the fuel in the reservoir (3);
fuel injection pressure change detecting means (20) for detecting the actual value of the difference of the pressures in the reservoir (3) before and after the fuel injection from the fuel injection valve (1) based on the pressures detected by the pressure detecting means (31) before and after the fuel injection;
fuel injection pressure change estimating means (20) for calculating an estimated value of the difference of the pressures in the reservoir (3) before and after the fuel injection from the fuel injection valve (1) based on a target value of the fuel injection amount and a bulk modulus of elasticity of the fuel;
first means (20) for calculating a first characteristic value representing whether the fuel injection system has failed based on the actual value and the estimated value of the difference of the pressures in the reservoir (3) before and after the fuel injection;
fuel feed pressure change detecting means (20) for detecting the actual value of the difference of the pressures in the reservoir (3) before and after the fuel feed from the fuel pump based on the pressures detected by the pressure detecting means (31) before and after the fuel feed from the fuel pump (5);
fuel feed pressure change estimating means (20) for calculating an estimated value of the difference of the pressures in the reservoir (3) before and after the fuel feed from the fuel pump (5) based on a target value of the fuel feed amount and the bulk modulus of elasticity of the fuel; and
second means (20) for calculating a second characteristic value representing whether the fuel injection system has failed based on the actual value and the estimated value of the difference of the pressures in the reservoir (3) before and after the fuel feed,
and that said failure determining means (20) determines whether the fuel injection system has failed based on said first and second characteristic values.

6. A fuel injection system as set forth in claim 5, wherein said first characteristic value is a difference between the actual value and the estimated value of the difference of the pressures in the reservoir (3) before and after the fuel injection, and said second characteristic value is a difference between the actual value and the estimated value of the difference of the pressure in the reservoir (3) before and after the fuel feed.

7. A fuel injection system as set forth in claim 6, wherein said failure determining means (20) further comprises first preliminary determining means (20) for determining whether the fuel injection system has failed by comparing the first characteristic value with a predetermined first reference value and second preliminary determining means (20) for determining whether the fuel injection system has failed by comparing the second characteristic value with a predetermined second reference value and, wherein said failure determining means (20) determines that the fuel injection system has failed only when both the first and the second preliminary determining means determine that the fuel injection system has failed.

8. A fuel injection system as set forth in claim 6, wherein said failure determining means (20) determines whether the fuel injection system has failed by comparing the sum of the first and the second characteristic values with a predetermined reference value.

9. A fuel injection system as set forth in claim 6, further comprising bulk modulus calculating means (20) for calculating the bulk modulus of elasticity of the fuel in the reservoir (3) based on the difference between the first and the second characteristic values.

Fig.1

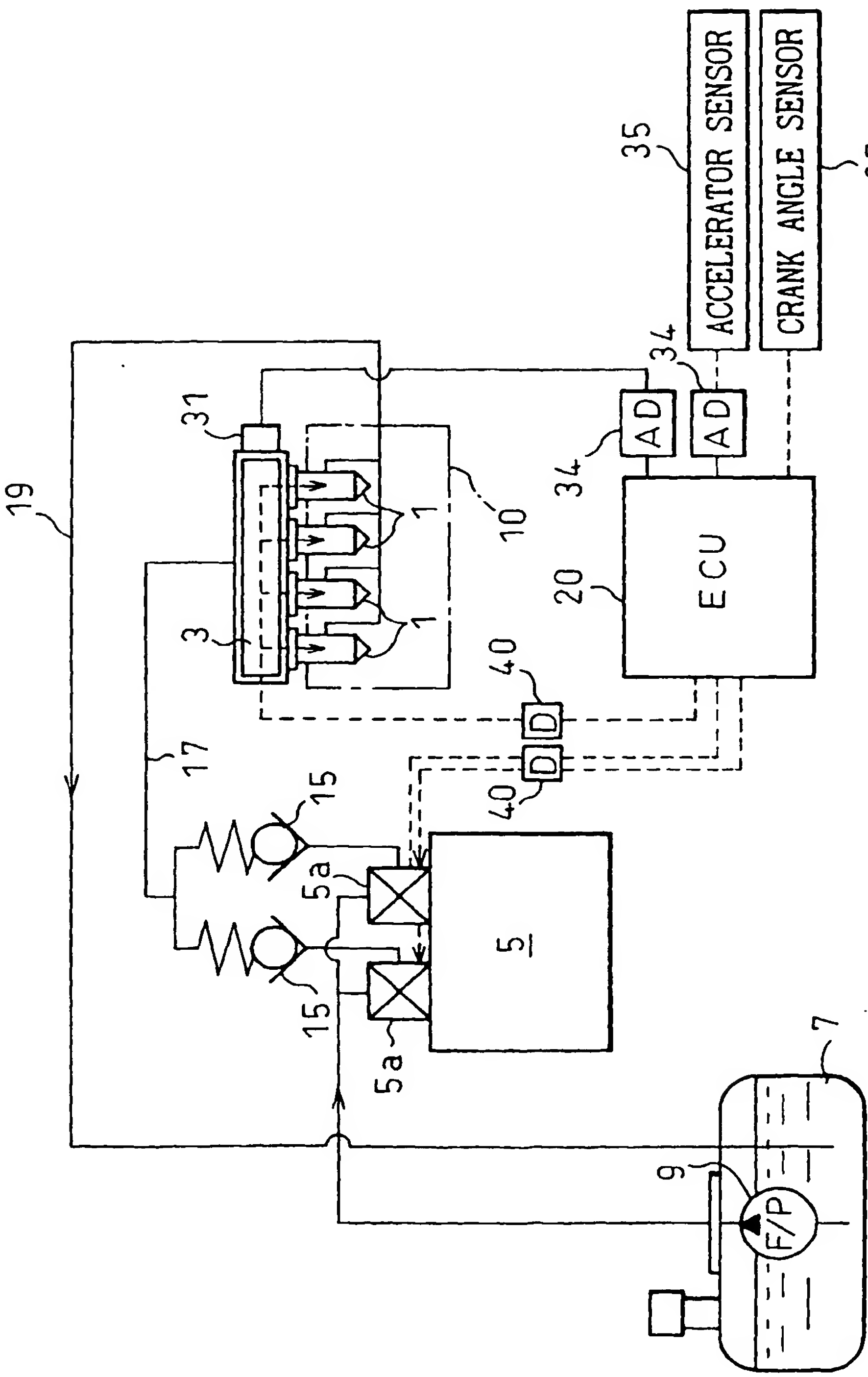
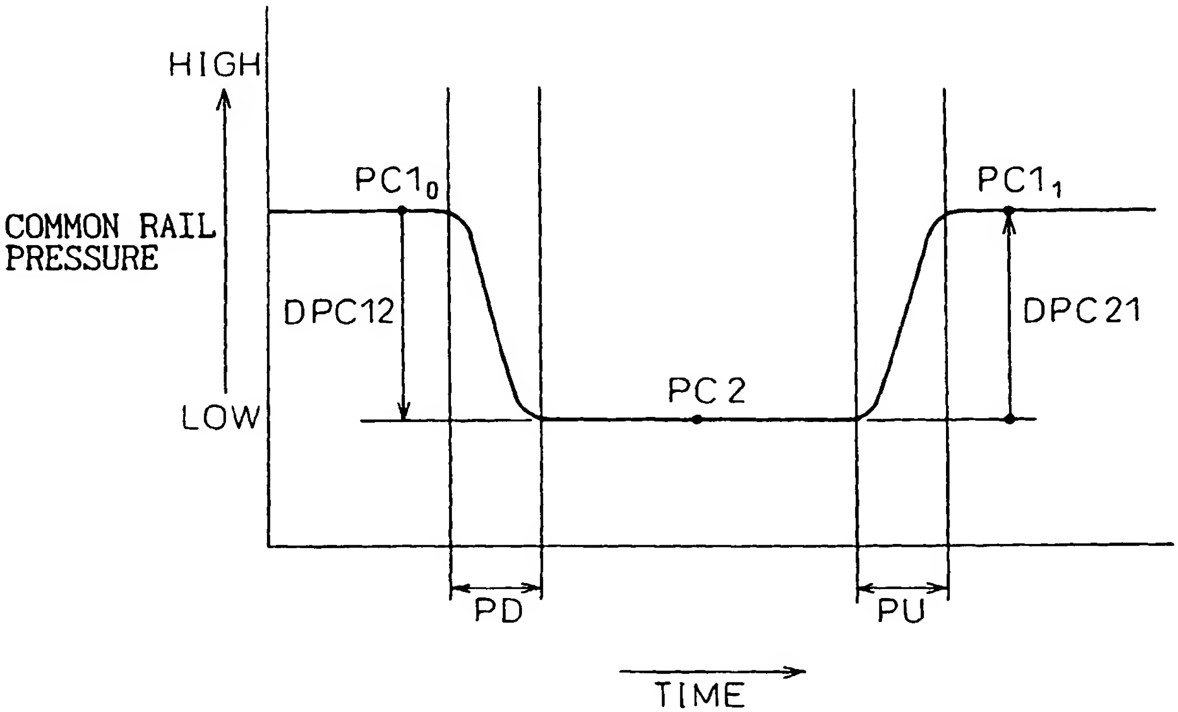

ACCELERATOR SENSOR
CRANK ANGLE SENSOR
ECU
AD
AD
D
D
F/P
35
37
34
34
31
19
10
1
1
3
20
40
40
17
15
15
5a
5a
5
7
9

Fig. 2



DPC12=PC2-PC1$_0$
DPD: ESTIMATED VALUE OF PRESSURE DROP
DPDJC=DPD-DPC12

DPC21=PC1$_1$-PC$_2$
DPU: ESTIMATED VALUE OF PRESSURE RISE
DPUJC=DPU-DPC21

Fig. 3

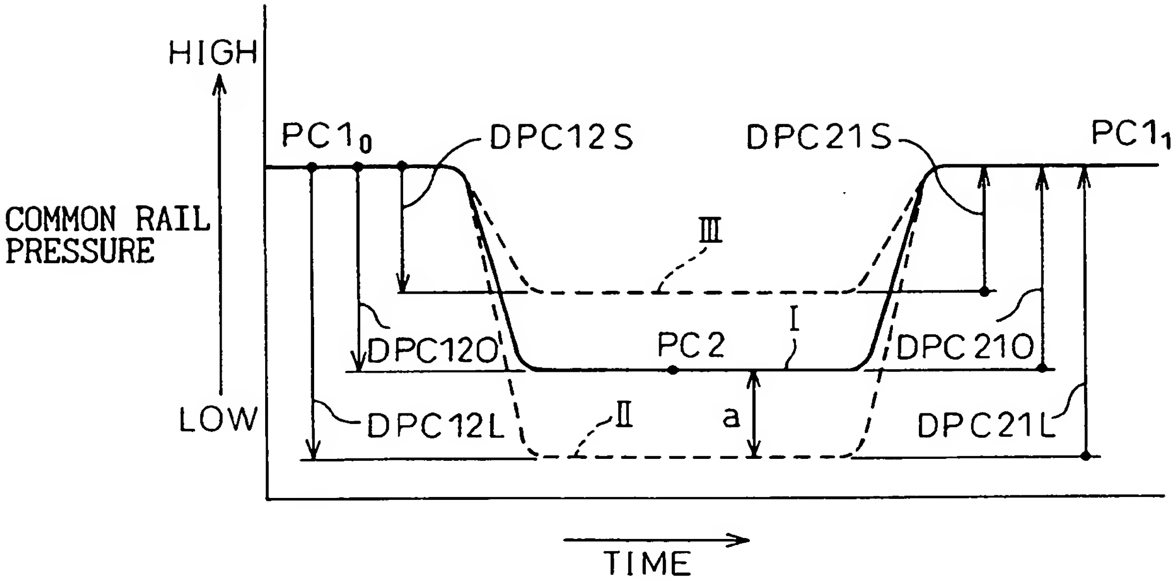

HIGH
COMMON RAIL PRESSURE
LOW
TIME
PC1₀
DPC12S
DPC21S
PC1₁
III
I
DPC120
PC2
DPC210
II
a
DPC12L
DPC21L

Fig. 4

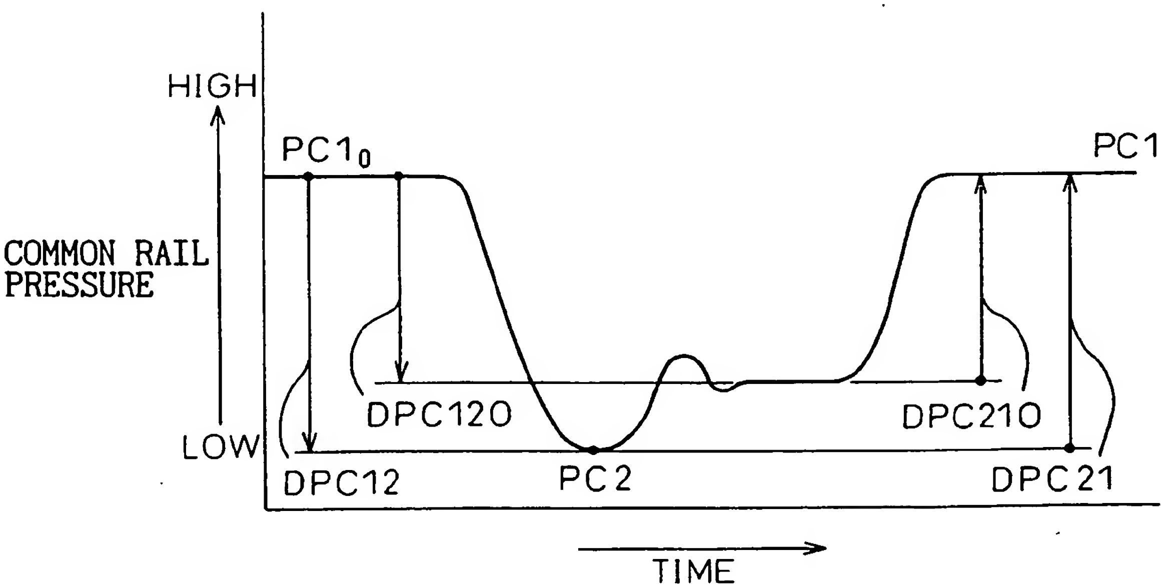

HIGH
COMMON RAIL PRESSURE
LOW
TIME
PC1₀
PC1₁
DPC120
DPC210
DPC12
PC2
DPC21

Fig. 5

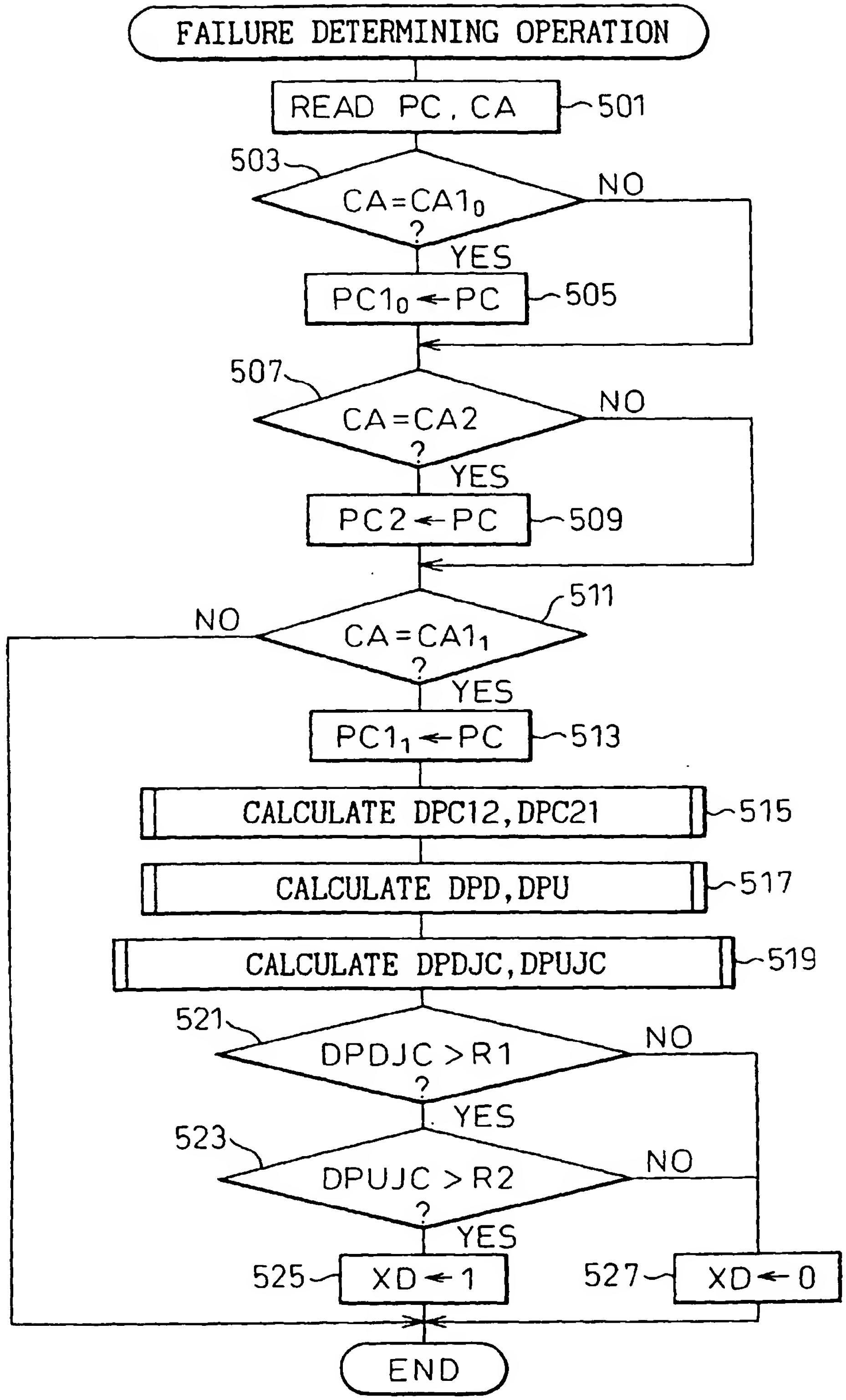

FAILURE DETERMINING OPERATION
READ PC, CA
501
503
CA=CA1₀ ?
NO
YES
PC1₀←PC
505
507
CA=CA2 ?
NO
YES
PC2←PC
509
511
NO
CA=CA1₁ ?
YES
PC1₁←PC
513
CALCULATE DPC12, DPC21
515
CALCULATE DPD, DPU
517
CALCULATE DPDJC, DPUJC
519
521
DPDJC>R1 ?
NO
YES
523
DPUJC>R2 ?
NO
YES
525
XD←1
527
XD←0
END

Fig. 6

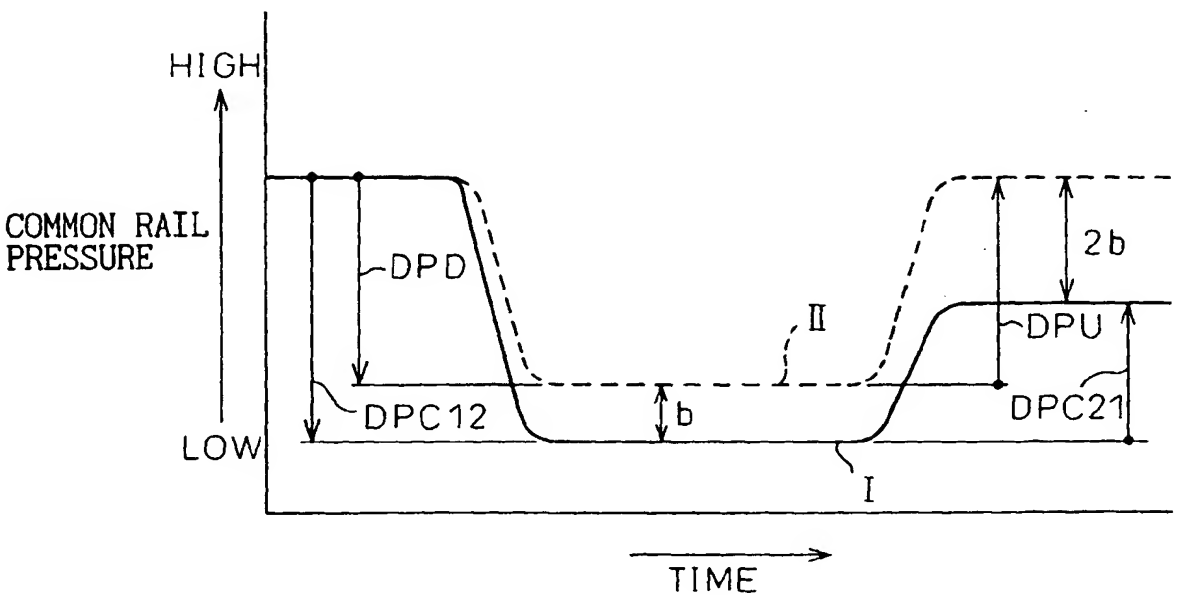

HIGH
COMMON RAIL
PRESSURE
LOW
DPD
DPC12
b
II
I
2b
DPU
DPC21
TIME

Fig. 7

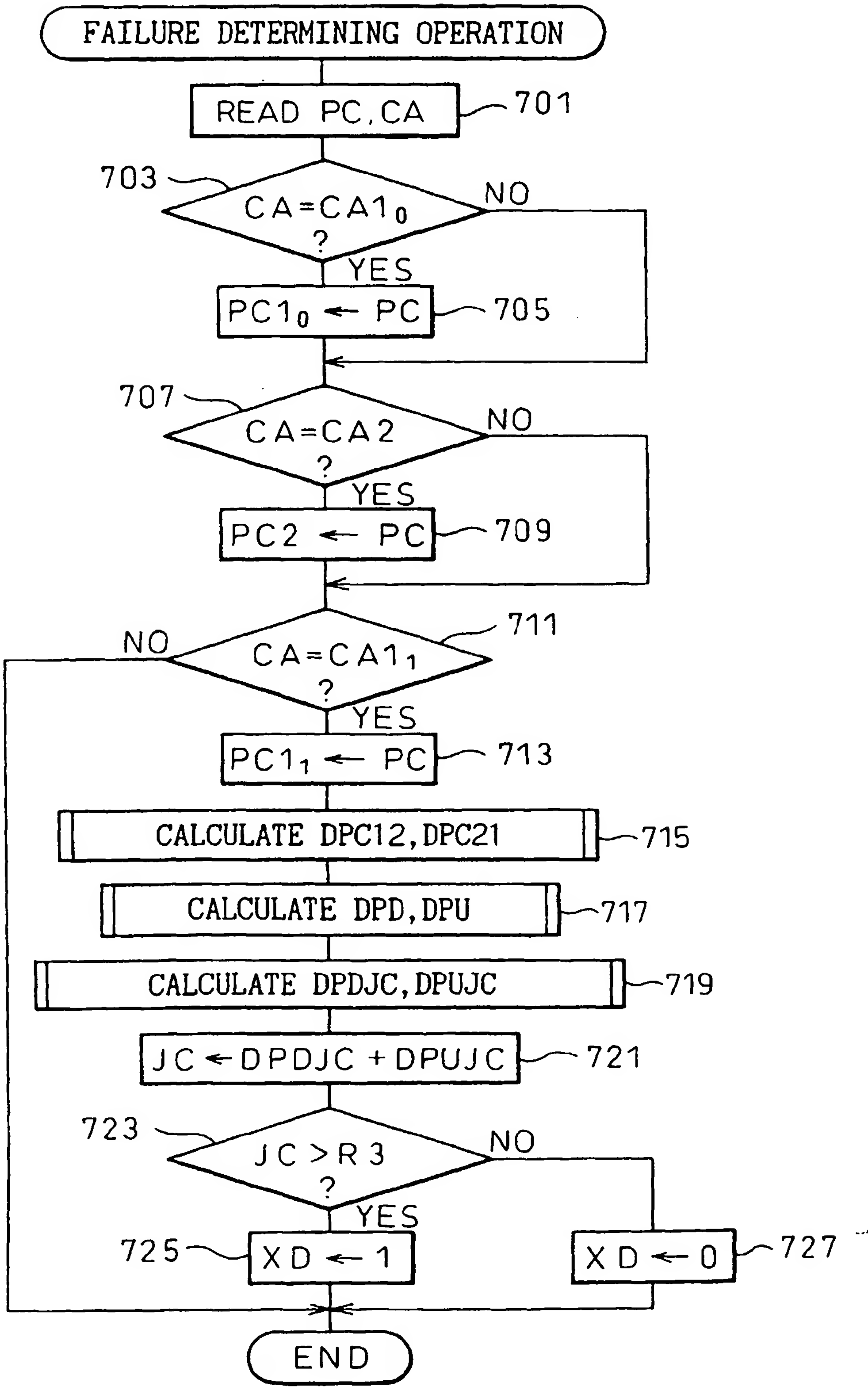

FAILURE DETERMINING OPERATION
READ PC, CA
701
703
CA=CA1₀ ?
NO
YES
PC1₀ ← PC
705
707
CA=CA2 ?
NO
YES
PC2 ← PC
709
711
NO
CA=CA1₁ ?
YES
PC1₁ ← PC
713
CALCULATE DPC12, DPC21
715
CALCULATE DPD, DPU
717
CALCULATE DPDJC, DPUJC
719
JC ← DPDJC + DPUJC
721
723
JC > R3 ?
NO
YES
725
XD ← 1
XD ← 0
727
END

Fig. 8

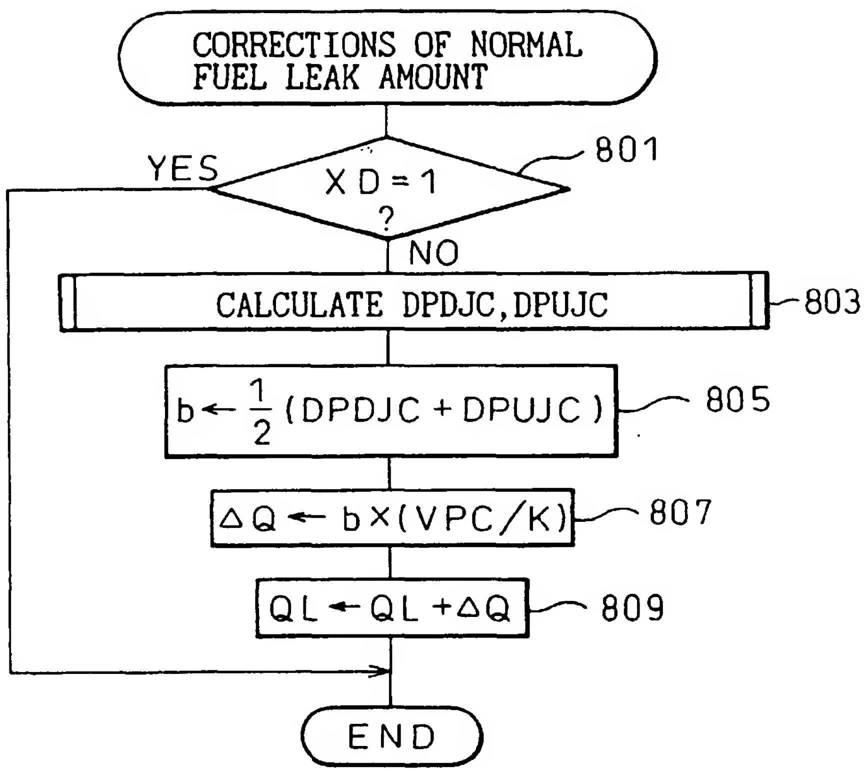

CORRECTIONS OF NORMAL FUEL LEAK AMOUNT
801
XD = 1 ?
YES
NO
CALCULATE DPDJC, DPUJC
803
b ← 1/2 (DPDJC + DPUJC)
805
ΔQ ← b×(VPC/K)
807
QL ← QL +ΔQ
809
END

Fig. 9

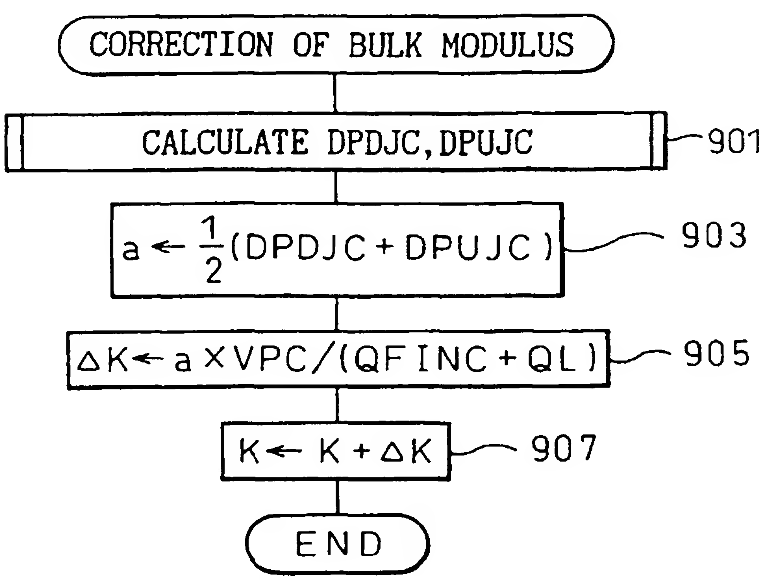

CORRECTION OF BULK MODULUS
CALCULATE DPDJC, DPUJC
901
a ← 1/2 (DPDJC + DPUJC)
903
ΔK ← a×VPC/(QFINC + QL)
905
K ← K + ΔK
907
END

Fig. 10

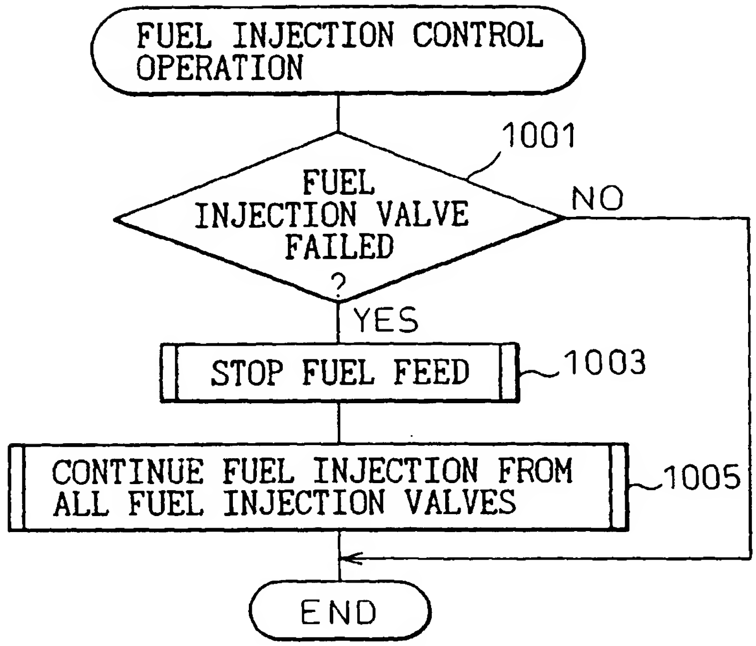

FUEL INJECTION CONTROL OPERATION
1001
FUEL INJECTION VALVE FAILED ?
NO
YES
STOP FUEL FEED
1003
CONTINUE FUEL INJECTION FROM ALL FUEL INJECTION VALVES
1005
END

Fig. 11

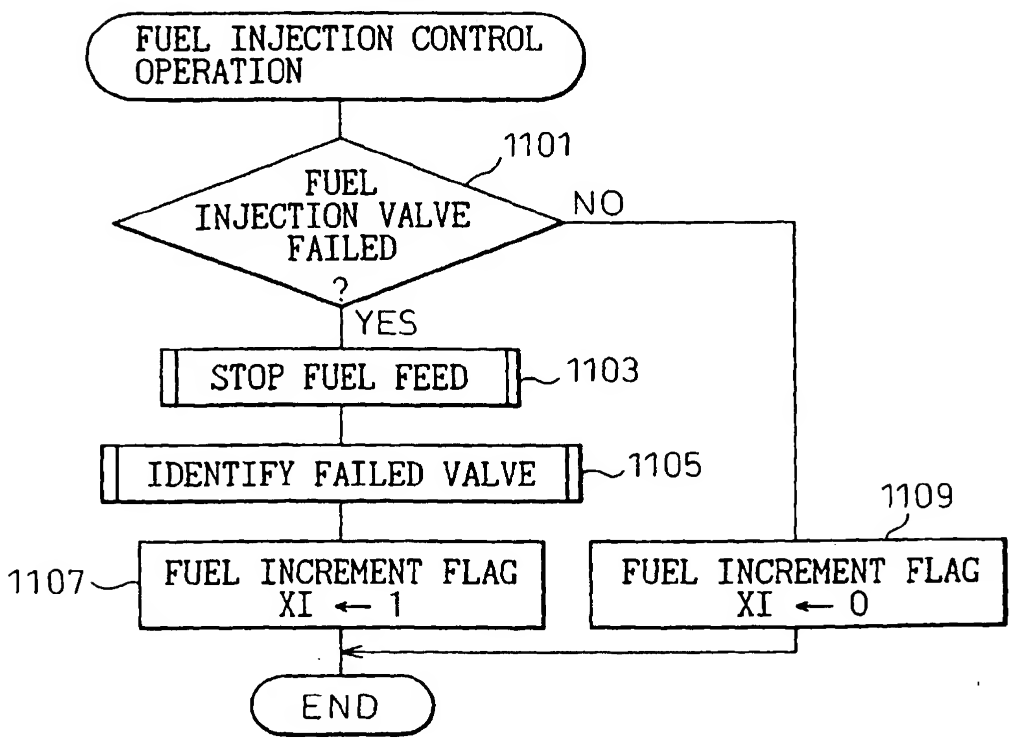
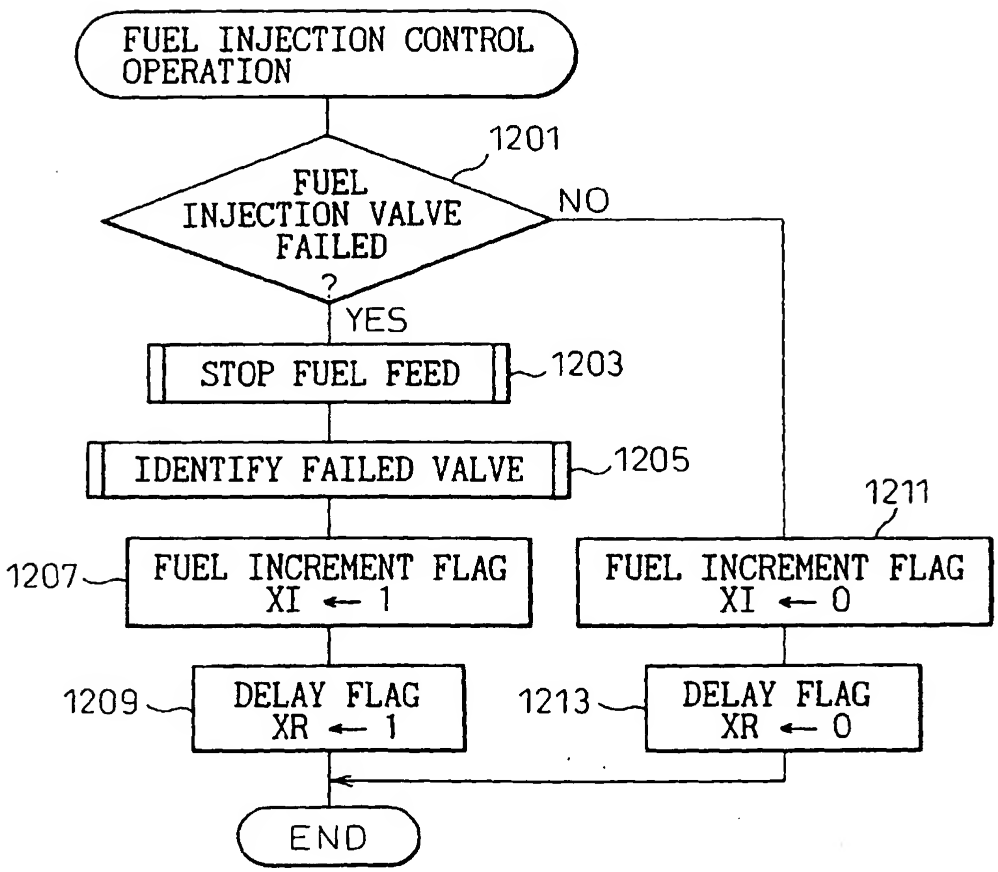

FUEL INJECTION CONTROL OPERATION
1101
FUEL INJECTION VALVE FAILED ?
NO
YES
STOP FUEL FEED
1103
IDENTIFY FAILED VALVE
1105
1109
1107
FUEL INCREMENT FLAG XI ← 1
FUEL INCREMENT FLAG XI ← 0
END

Fig. 12


FUEL INJECTION CONTROL OPERATION
1201
FUEL INJECTION VALVE FAILED ?
NO
YES
STOP FUEL FEED
1203
IDENTIFY FAILED VALVE
1205
1211
1207
FUEL INCREMENT FLAG XI ← 1
FUEL INCREMENT FLAG XI ← 0
1209
DELAY FLAG XR ← 1
1213
DELAY FLAG XR ← 0
END

(19) Eur päisches Patentamt
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Offic uropéen des brevets

(11) EP 0 860 600 A3

(12) EUROPEAN PATENT APPLICATION

(88) Date of publication A3:
29.03.2000 Bulletin 2000/13

(43) Date of publication A2:
26.08.1998 Bulletin 1998/35

(21) Application number: 98102890.5

(22) Date of filing: 19.02.1998

(51) Int. Cl.[7]: F02D 41/38, F02D 41/20

(84) Designated Contracting States:
AT BE CH DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(30) Priority: 21.02.1997 JP 3797997
26.02.1997 JP 4241197

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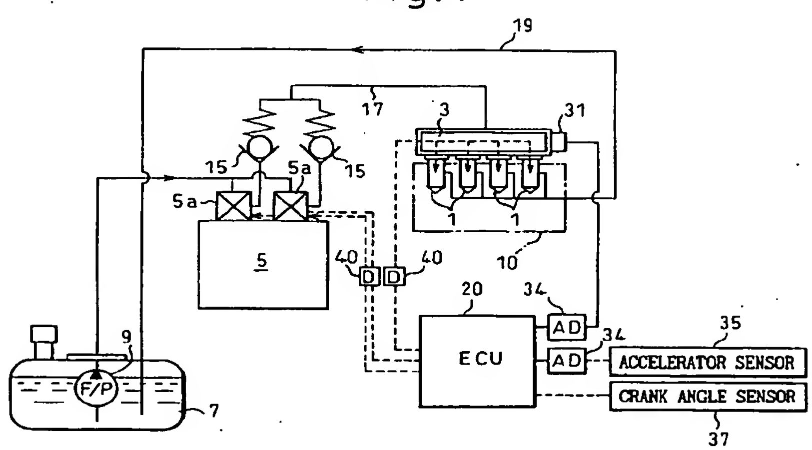
(54) A fuel injection system for an internal combustion engine

(57) Fuel injection valves (1) of the engine (10) are connected to the common rail (3). The high pressure fuel pump (5) supplies pressurized fuel to the common rail (3). The electronic control unit (ECU) (20) determines whether one or more of the fuel injection valves has failed. When one or more of the fuel injection valves is determined as having failed, the ECU stops the high pressure fuel pump and injects fuel from all of the fuel injection valves including the fuel injection valve determined as being failed. Since the fuel remained in the common rail is expelled from the common rail through, not only the failed fuel injection valve, but also other fuel injection valves, the common rail is depressurized in a short time and, thereby, the abnormal fuel injection from the failed fuel injection valve stops in a short time.

Fig.1



Printed by Xerox (UK) Business Services
2.16.7/3.6

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EUROPEAN SEARCH REPORT

Application Number
EP 98 10 2890

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
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Y	US 4 704 997 A (BEPPU OSAMU ET AL) 10 November 1987 (1987-11-10) * column 1, line 64 - column 2, line 2 * * column 3, line 14 - line 25 * * figures 1-4 * ---	1	
A	EP 0 501 459 A (NIPPON DENSO CO) 2 September 1992 (1992-09-02) * column 3, line 30 - line 45 * ---	1	TECHNICAL FIELDS SEARCHED (Int.Cl.6) F02D
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A	* abstract * --- -/--	1,8	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	20 January 2000	De Vita, D

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EPO FORM 1503 03.82 (P04C01)

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 98 10 2890

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	EP 0 748 930 A (DAIMLER BENZ AG) 18 December 1996 (1996-12-18) * column 3, line 10 - column 4, line 33 * * figures 2,3 *	5-8	
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E	EP 0 860 601 A (TOYOTA MOTOR CO LTD) 26 August 1998 (1998-08-26) * page 3, line 5 - line 12 * * page 5, line 11 - page 6, line 9 * * figures 2,3 * * claims 1,4 *	5-9	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	20 January 2000	De Vita, D

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Application Number
EP 98 10 2890

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing more than ten claims.

☐ Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims and for those claims for which claims fees have been paid, namely claim(s):

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

☒ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

☐ None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

European Patent Office

LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 98 10 2890

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. Claims: 1-4

   Common Rail with depressurating means in case of fuel injection valves failure.

2. Claims: 5-9

   Comon Rail system with failure determining means using fuel injection pressure changes as criteria for determination of system failure.

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 98 10 2890

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